North Pacific Acoustic Laboratory: Scripps Institution of Oceanography

Peter F. Worcester
Scripps Institution of Oceanography, University of California, San Diego
La Jolla, CA 92093-0225
phone: (858) 534-4688 fax: (858) 534-6251 email: pworcester@ucsd.edu

Co-Investigators
Bruce D. Cornuelle
Scripps Institution of Oceanography, University of California, San Diego
La Jolla, CA 92093-0230
phone: (858) 534-4021 fax: (858) 534-9820 email: bcornuelle@ucsd.edu

Matthew A. Dzieciuch
Scripps Institution of Oceanography, University of California, San Diego
La Jolla, CA 92093-0225
phone: (858) 534-7986 fax: (858) 534-6354 email: mdzieciuch@ucsd.edu

Walter H. Munk
Scripps Institution of Oceanography, University of California, San Diego
La Jolla, CA 92093-0225
phone: (858) 534-2877 fax: (858) 534-6251 email: wmunk@ucsd.edu

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LONG-TERM GOALS

The North Pacific Acoustic Laboratory (NPAL) program is intended to improve our understanding of (i) the basic physics of low-frequency, broadband propagation in deep water, including the effects of oceanographic variability on signal stability and coherence, (ii) the structure of the ambient noise field in deep water at low frequencies, and (iii) the extent to which acoustic methods, together with other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for acoustic predictions. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.

OBJECTIVES

A series of deep-water acoustic propagation experiments have been conducted in the North Pacific Ocean during the last 20 years using various combinations of low-frequency, wide-bandwidth transmitters and horizontal and vertical line array receivers (Worcester and Spindel, 2005). Each experiment had its own specific objectives. The scientific objectives of the most recent NPAL experiment, which was conducted in the central North Pacific during 2004–2005, were:

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14. ABSTRACT
The North Pacific Acoustic Laboratory (NPAL) program is intended to improve our understanding of (i) the basic physics of low-frequency, broadband propagation in deep water, including the effects of oceanographic variability on signal stability and coherence, (ii) the structure of the ambient noise field in deep water at low frequencies, and (iii) the extent to which acoustic methods, together with other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for acoustic predictions. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.

15. SUBJECT TERMS

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- To explore the range and frequency dependence of the fluctuation statistics and coherence (vertical and temporal) of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments

- To understand the surprisingly large amount of acoustic scattering into the geometric shadow zones beneath caustics previously seen with bottom-mounted SOSUS receivers

- To elucidate the relative roles of internal waves, ocean spice, and internal tides in causing acoustic fluctuations

- To study acoustic scattering and diffraction from bathymetry

- To improve basin-scale ocean now-casts via assimilation of acoustic travel-time and other data into models

- To document the spatial and temporal variability of ambient noise on ocean basin scales

APPROACH

SIO participates both in the conduct of the NPAL experiments and in the analysis of the resulting data. The most recent NPAL experiment consisted of three closely related components: SPICEX (Spice Experiment), LOAPEX (Long-range Ocean Acoustic Propagation Experiment), and BASSEX (Basin Acoustic Seamount Scattering Experiment). SIO was responsible for SPICEX, for which two 250-Hz broadband acoustic transceiver moorings and two autonomous vertical line array (VLA) receivers were installed. The transceiver moorings were deployed 500 and 1000 km from the VLA receivers, which combined spanned much of the water column. In addition, the sources provided signals that were recorded on a towed horizontal array for BASSEX, and the VLAs were the primary receivers for transmissions made with a 75-Hz source suspended from shipboard for LOAPEX.

Essential components of the various NPAL experiments are extensive measurements to characterize the environment through which the sound propagates. In the 2004–2005 experiment, Underway CTD (UCTD) measurements were made along the path between the VLA receivers and moored sources, providing high-resolution measurements of the upper ocean. These data are being used to separate the sound-speed fine structure into two component fields: (i) isopycnal tilt dominated by internal waves and (ii) “spicy” (cold-fresh to hot-salty) millifronts associated with upper ocean stirring, so that the relative roles of internal waves and spice in the scattering of the NPAL transmissions can be evaluated. A number of deep CTD casts were also made. Finally, a Seaglider autonomous vehicle deployed by APL-UW during the LOAPEX cruise made measurements along the path beginning in September, before transiting to Kauai for recovery.

In order to understand the observed receptions, simulations are made with parabolic equation (Collins, 1993) and other acoustic propagation models using realistic models of internal wave and other oceanographic variability for comparison with the observations.

WORK COMPLETED

We worked on a number of different tasks during FY2007:

NPAL98 Analysis. During FY2007 we finally had in place all of the tools needed to compute the horizontal coherence of *resolved* ray arrivals for the billboard array data collected in the 1998–1999 NPAL experiment. Determining the horizontal coherence was one of the fundamental goals of this experiment. The measured horizontal coherences were compared with the results from parabolic equation simulations and with the predictions of path-integral theory, both of which were provided by Vera (2007).

SPICEX Analysis. We continued analysis of the SPICEX data. L. Van Uffelen, who is now supported by an ONR Graduate Traineeship, is taking the lead in examining the shadow-zone arrivals seen in the 250-Hz receptions on the Shallow and Deep VLA receivers. She is working to determine the relative roles of different sources of oceanic variability, including internal waves, ocean spice, and reflections off the base of the oceanic mixed layer (Rudnick and Munk, 2006), in contributing to the observed vertical scattering. Her results are summarized in a separate ONR annual report describing progress on her ONR Graduate Traineeship, entitled “Vertical Structure of Shadow Zone Arrivals: Comparison of Parabolic Equation Simulations and Acoustic Data.”

Travel-time Sensitivity Kernel (TSK). We continued development of the wave-theoretic travel-time sensitivity kernel (TSK) analysis pioneered by Skarsoulis and Cornuelle (2004), including calculations to determine the effect of internal-wave-induced scattering on the TSK.

Acoustic Thermometry. We continued analysis of the nearly decade-long time series of acoustic measurements of large-scale, depth-averaged temperature in the North Pacific Ocean obtained by the Acoustic Thermometry of Ocean Climate (ATOC) and NPAL projects, working closely with B. Dushaw (APL-UW). The acoustic measurements were compared with analyses combining altimetric and in situ profile data (Willis et al., 2003, 2004, 2007; Lyman et al., 2006) and with results from the Estimating the Circulation and Climate of the Ocean (ECCO) (Marshall et al., 1997) and Parallel Ocean Program (POP) (Maltrud and McClean, 2005) ocean general circulation models (OGCM).

Modern ocean general circulation models, such as the ECCO and POP models, have the vertical resolution needed for acoustic propagation calculations, allowing straightforward comparison of measured and predicted travel times as a first step in using the acoustic data to constrain the models.

Comparison of the model results with the naturally integrating long-range acoustic transmissions provides stringent tests of the accuracy of the mean states and large-scale, low frequency variability in the models. Our results are summarized in a separate ONR annual report submitted by B. Dushaw, entitled “North Pacific Acoustic Laboratory: Analysis of Shadow Zone Arrivals and Acoustic Propagation in Numerical Ocean Models.”

NPAL Special Session. Results from the 2004–2005 NPAL experiment were presented in a special session at the 152nd Meeting of the Acoustical Society of America in Honolulu, Hawaii, 28 November – 02 December 2006.

Philippine Sea Deep-Water Propagation Experiment Preparations. During FY2007 we were heavily engaged in planning and preparing for the next NPAL experiment, which is to be conducted in the northern Philippine Sea during 2010–2011, preceded by a Pilot Study/Engineering Test during April-May 2009. In this experiment we will be moving to a new ocean environment and somewhat shorter ranges than those used in past NPAL experiments. The Philippine Sea is modulated by significant eddy variability moving in from the east. A strong western boundary current, the Kuroshio, is to the west,

just east of Taiwan. Measurements of acoustic propagation and ambient noise will be combined with the use of acoustic remote sensing methods to help characterize this highly dynamic region.

With DURIP funding, we are developing a new vertical line array receiver capable of spanning the full water column in deep water and acquiring a new very low frequency (140–190 Hz) swept frequency source being developed by Webb Research Corporation. The development of the VLA is particularly critical to the conduct of the experiment. The acoustic propagation experiments that have been performed in recent years have been constrained by the lack of VLA receivers capable of spanning the full water column. Such arrays are required to enable the separation of acoustic modes using spatial filtering and to fully characterize the acoustic time fronts formed in deep water propagation. During the past year we have begun the design of a modular, Distributed VLA (DVLA) capable of being extended to cover the full water column in water up to about 5000 m deep. We are developing a novel approach using self-recording hydrophones with timing and scheduling provided by a small number of our existing STAR data acquisition systems and controllers. Inductively coupled modems will connect the STAR controllers to the self-recording hydrophones, using standard oceanographic mooring wire.

Quantifying, Predicting, and Exploiting Uncertainty DRI. During FY2007 Cornuelle and Worcester participated in planning for the QPE DRI. Cornuelle's efforts are summarized in a separate ONR annual report, entitled "Planning for an Experiment Combining Acoustic and Other Data with Regional Ocean Models in the Philippine Sea." Worcester participated in the three DRI planning meetings, making presentations on the complementary deep-water NPAL experiment being planned for the northern Philippine Sea. It appears that the principle link between the QPE DRI and the NPAL Group will be through the application of data assimilation into a regional ocean model to estimate the evolving state of the northern Philippine and East China Seas, for use in acoustic propagation calculations.

RESULTS

Results for the horizontal coherence from the NPAL98 experiment and from the TSK development are shown here. Results from our other work during FY2007 are available in the ONR annual reports mentioned above.

Horizontal coherence. For the NPAL98 experiment, five VLA receivers were deployed off central California in a line transverse to the propagation path of acoustic signals transmitted by a broadband 75-Hz source located north of Kauai, 3500 km away. The horizontal coherence of the entire received signal has been computed (Voronovich et al., 2005), but it has been difficult to analyze the horizontal coherence of resolved ray arrivals because of the low signal-to-noise ratio and because a large portion of the arrival energy is bottom interacting. Using the turning point filter to enhance the SNR (Dzieciuch et al., 2001) and with careful tracking of the resolved arrivals, however, it is now possible to find at least four arrivals that are relatively free from bottom interference.

Not surprisingly, the horizontal coherence of the four resolved acoustic arrivals is substantially greater than that of the received signal as a whole, which is reduced by interference effects between the various ray arrivals (Fig. 1). Significant coherence remains at the maximum available separation of about 3500 m. The measured coherence is also greater than that computed from parabolic equation simulations using the Garrett-Munk internal wave model and from the predictions of path integral theory, both of which were provided by Vera (2007). One could decrease the internal wave energy level in the simulations to make the simulations match the data, but then the ocean becomes unrealistic.

This calls into question the validity of the scattering models used. An alternate approach using the TSK is now being developed.

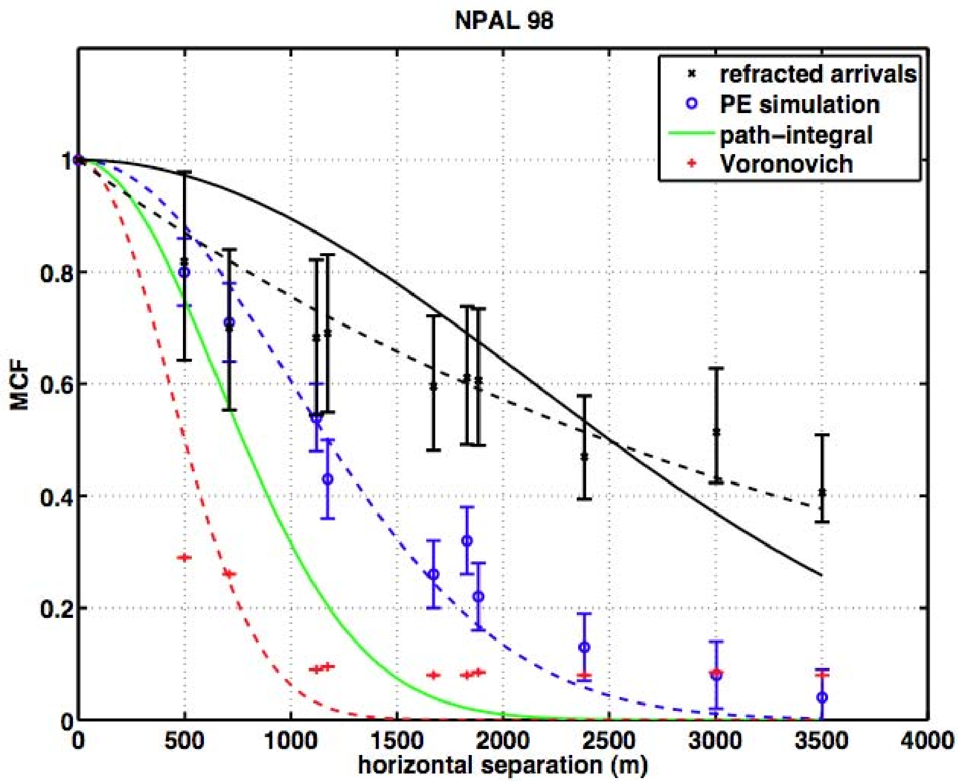

Fig. 1. The horizontal coherence (Mutual Coherence Function, MCF) of four resolved ray arrivals for the NPAL98 experiment. The measured coherence falls to about 0.4 at a horizontal separation of 3500 m (black stars with error bars). Parabolic equation simulations (blue) and path integral theory (green) using the Garrett-Munk internal wave model both predict substantially shorter horizontal coherence lengths, falling to 0.4 at about 1300 m and 900 m separation, respectively. The horizontal coherence of the entire received signal is only 0.3 at 500 m separation (red), which is the smallest separation available. Various fits to the data are also shown (black solid, black dashed, and red dashed.)

Full-wave Acoustic Sensitivity Kernels. Ray theory has long been the model used when trying to reconcile ocean acoustic measurements with environmental parameters. For ocean acoustic tomography, measured travel time changes are ascribed to sound-speed changes along the unperturbed ray path. Since sound is governed by the wave equation, the travel time can be affected by environmental changes that are not on the geometric ray path, however. The goal of this work is to understand the extent to which this happens and to determine the validity of the ray approximation.

The full-wave acoustic sensitivity kernel is a map in physical space of the change in the acoustic measurement for a given change in environmental parameters (the Frechet derivative). This could be calculated by brute force, but a mathematical formulation of the problem relying on the Born approximation and the principle of reciprocity allows a much simpler (although still challenging) computational problem (Skarsoulis and Cornuelle, 2004). We have extended this work to include the effects of range dependence and can now calculate the kernel using the RAM parabolic equation

propagation code (Collins, 1993) for much more realistic ocean environments, including internal waves, for example. Mean and rms travel-time sensitivity kernels calculated when internal wave scattering is added to the environment shows that the geometric ray model is a reasonable one in many situations, depending on the scale sizes of the perturbations.

The TSK can be used to help interpret the way in which the non-geometric shadow zone arrivals recently measured in the NPAL 2004 experiment sample the ocean. A simulated example is shown in Figure 2. The arrow points to an arrival at a receiver at 3500 m depth, below the lower turning point of the geometric ray arrival. The relative roles of different sources of oceanic variability, including internal waves, ocean spice, and reflections off the base of the oceanic mixed layer (Rudnick and Munk, 2006), in contributing to the observed vertical scattering are still being sorted out.

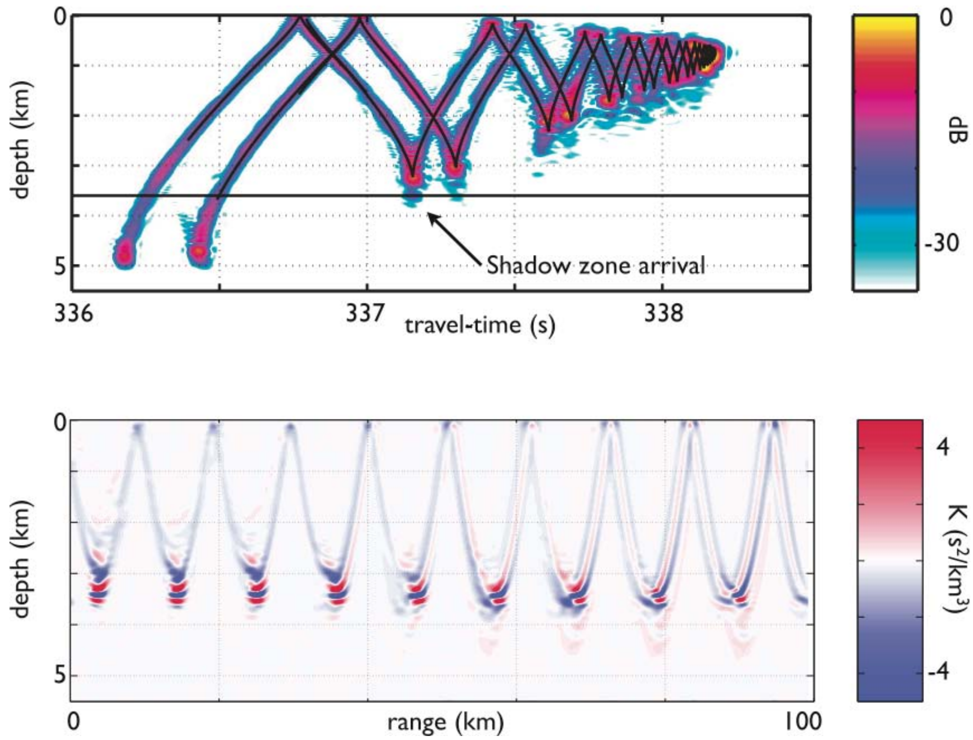

Fig. 2. (Top) The time front at 500 km range for a 75-Hz, Q=4 source at 750 m depth computed using the parabolic equation propagation code with the Garrett-Munk internal wave spectrum. The black line shows the time front in the geometric optics approximation without internal waves. (Bottom) The sensitivity as a function of range and depth of the travel time of a resolved shadow-zone arrival for a receiver at 3500 m depth to changes in sound speed. Only the first 100 km of the path is shown. Alternating blue and red colors show zones of negative and positive sensitivity with negative sensitivity along the ray path as expected.

IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior. The data indicate that existing systems do not begin to exploit the ultimate limits to acoustic coherence at long range in the ocean.

TRANSITIONS

Simple Tomographic Acoustic Receiver (STAR). The Naval Postgraduate School (NPS) previously used two of the Simple Tomographic Acoustic Receiver (STAR) data acquisition systems developed by my group at SIO in the Windy Island Soliton Experiment (WISE). The STAR systems are much more cost-effective and significantly easier to use than previous generations of acoustic receivers employed in long-range propagation and ocean acoustic tomography experiments. NPS was so pleased with the performance of the STAR systems that they purchased a STAR Deck Unit from us during this past year, as the first step in a long-term plan to acquire STAR systems to be used in their future research.

In addition, the Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway, is funded in the framework of the European Union DAMOCLES project to develop an ocean acoustic tomography system for monitoring the average heat content across Fram Strait at 78°50'N. After reviewing various possible approaches to developing an ocean acoustic tomography system, NERSC decided to purchase two STARs from my group. In addition, NERSC decided to purchase a swept-frequency acoustic source (190–290 Hz) from Webb Research Corporation, which in turn ordered a third STAR from us to serve as the controller for the source. The tomographic system is scheduled for initial deployment during October 2007 on the eastern side of Fram Strait, with recovery during summer 2008. A subsequent deployment is tentatively planned during 2008–2009 on the western side of the Strait.

RELATED PROJECTS

A large number of investigators and their students are currently involved in ONR-supported research related to the NPAL project. The Principal Investigators include R. Andrew (APL-UW), A. Baggeroer (MIT), F. J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), B. Dushaw (APL-UW), S. Flatté (UCSC), N. Grigorieva (St. Petersburg State Marine Technical Univ.), K. Heaney (OASIS), F. Henyey (APL-UW), B. Howe (APL-UW), J. Mercer (APL-UW), A. Morozov (WRC and WHOI), V. Ostachev (NOAA/ETL), D. Rudnick (SIO), E. Skarsoulis (IACM/FORTH), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), and M. Wolfson (APL-UW).

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